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Status and Needs of Power Electronics for Photovoltaic Inverters: Summary Document

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ABSTRACT

Photovoltaic inverters are the most mature of any DER inverter, and their mean time to first failure (MTFF) is about five years. This is an unacceptable MTFF and will inhibit the rapid expansion of PV. With all DER technologies, (solar, wind, fuel cells, and microturbines) the inverter is still an immature product that will result in reliability problems in fielded systems. The increasing need for all of these technologies to have a reliable inverter provides a unique opportunity to address these needs with focused R&D development projects. The requirements for these inverters are so similar that modular designs with universal features are obviously the best solution for a 'next generation' inverter. A 'next generation' inverter will have improved performance, higher reliability, and improved profitability. Sandia National Laboratories has estimated that the development of a 'next generation' inverter could require approximately 20 man-years of work over an 18- to 24-month time frame, and that a government-industry partnership will greatly improve the chances of success.

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1 Introduction

One milestone in the DOE Five-Year Photovoltaic Program Plan (2000-2004) is to "evaluate balance-of-systems component progress and future needs." This document is intended to meet that milestone with regards to inverters. While there are other Balance of System (BOS) needs, inverter problems continue to plague the industry and stand out as the salient BOS problem today. This report summarizes a more detailed report[1] that documents the progress of power electronics, identifies technologies that are in current use, and explores new approaches that can provide significant improvements in inverter reliability while leading to lower cost.

Today, the PV inverter is a costly and complex component of PV systems that produces ac power. Inverter mean time to first failure (MTFF) of about five years[2] is unacceptable. It is noted that the field data necessary to understand all inverter failure modes is not yet available; a separate Sandia program is addressing the field data problem. However, many of the shortcomings of inverters are known and it is clear that a program to advance inverter performance and reliability while minimizing inverter cost is timely. PV experience has shown that low inverter reliability contributes to unreliable fielded systems and a loss of confidence in renewable technology. The low volume of PV inverters produced has restricted the manufacturing to small suppliers without sophisticated reliability programs and manufacturing methods. Thus, the present approach to PV inverter supply has low probability of meeting DOE reliability goals.

The inverter problems are not a unique PV issue. Distributed Energy Resources (DER) sources such as wind, fuel cells, and microturbines all have inverters. Because fuel cells and microturbines are newer than PV, the pending problems with inverters are not widely understood. The increasing need in **all of these technologies** for a reliable inverter provides a unique opportunity to address these needs with a few focused R&D development projects. The inverter requirements are so similar that universal designs with replaceable modules are obviously the best solution for a 'next generation' inverter. For example, for all technologies the residential grid-tied inverter should be able to convert between 2 and 10 kilowatts of dc power, prevent islanding, reduce radio frequency interference, provide low harmonic distortion, and (optionally) provide backup power. Thus the residential, grid-tied inverters for solar, wind, and fuel cells can be nearly identical.

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[1] Status and Needs of Power Electronics for Photovoltaic Inverters, Sandia National Laboratories, Albuquerque, NM.

[2] R. Pitt, "Improving Inverter Quality," Proceedings, NCPV Program Review Meeting, April 16-19, 2000, Denver, CO, pp. 19-20.

No single approach for the inverter configuration stands out. The need to increase manufactured volume, however, suggests that some standardization should be employed. This has prompted the use of the term 'universal' inverter. The configuration could be a single box that performs all tasks, a single power section with various, interchangeable, dc-to-dc converters, or a building block concept similar to that used for personal computers. In the building block concept certain black boxes (e.g. a controller, a power converter, and so on) will be identical for various inverter configurations. Just as a computer can have varying amounts of memory, so the inverter could mix and match capabilities as required.

A next generation inverter will have improved performance, high reliability (10 years MTFF), and improved profitability. *It is not simply an improved version of what has not worked well; it is an order-of-magnitude move forward*. Such a development will have risk. Success is not guaranteed. Sandia has estimated that the development of a 'next generation' inverter could require approximately 20 man-years of work over an 18- to 24-month time frame. Companies with existing design and manufacturing capability could accomplish the task with fewer resources. The investment, however, is not small for most companies interested in the task. For that reason a government-industry partnership will greatly improve the chances of success.

What makes this initiative, the development of a 'next generation' inverter, timely is an increasing market and recent technology advances. Previously the government approach to improving inverter performance was limited to participating with small business in the *incremental* improvement of their product. At this time the market has expanded to the point where larger companies are interested, and the technologies, such as Digital Signal Processing (DSP) on a chip, allow major leaps that use software to accomplish tasks that have traditionally been performed by hardware. This permits wider application of a hardware product, resulting in even larger quantities of product. The final result is a much more reliable product. The timing is right for a major DER inverter initiative that will result in a quantum leap forward in technology. An essential requirement for this 'next generation' inverter will be a doubling of MTFF to ten years. The 'universal' inverter has been the 'holy grail' of inverter manufacturers for years; however, the advent of new technology and the increasing number of inverters being sold makes this next generation inverter an attainable goal now.

The need for better field data is a critical issue. Many of the problems that exist with inverters are known. These include design problems, manufacturing flaws, and poor management practices; these are the issues that the current inverter initiative intends to address. The next level of reliability will be reached by extensive analysis of field data that identifies continuing inverter problems. Three approaches to improving the reliability of a fielded system are[3]

- obtain a detailed knowledge of the inverter's working environment, its failure modes, and all failure mode causes, and feed this information back into redesigns,

[3] Personal Correspondence with Michael Ropp, Ph.D., South Dakota State University, Brookings SD, January 2002.

- over design, or
- redundancy.

The last two items increase cost, so it is particularly important that the amount of required over design and/or redundancy be accurately determined from field data. In all cases, the approach of obtaining accurate field data is essential.

Currently, there is a real shortage of reliable field data and acquiring accurate information will take considerable time. Sandia is in the process of developing a reliability program for PV and obtaining reliable field data for our database is a central element of that program. That program is just beginning and will be reported on in a separate document.

2 Summary of Hardware Status and Needs of PV Inverters

2.1 Hardware Status

PV inverters typically use an analog or an analog/micro-processor hybrid control system to control the power converter system. There are many problems associated with analog or analog/microprocessor hybrid control systems, for example, aging effect and temperature drift of analog devices, higher component count (this leads to shortened lifetime and quality), difficult and expensive field modifications, high cost, inflexible adoption to different electrical environments, low noise immunity, high electromagnetic interference (EMI), and an advanced control algorithm that is not easily implemented. Also, a separate micro-processor system has to be used for system monitoring and user interface. All of these problems contribute to the fact that existing power electronic converter systems for various renewable energy sources have MTFF of less than five years[4]. The following two paragraphs briefly discuss the current status of power electronics hardware.

2.1.1 Status of Power Semiconductor Devices

Today's progress in power electronics has been made possible primarily due to advances in power semiconductor devices. As the evolution of new and advanced semiconductor devices progressed, the voltage and current ratings and electrical characteristics of the existing devices began improving dramatically. Metal oxide semiconductor field effect transistors (MOSFETs) and insulated gate bi-polar transistors (IGBTs) have replaced the bi-junction transistor (BJT) almost completely. A remarkable development in MOSFETs took place during the last few years. The introduction of field effect transistors (S-FET) technology in 1996 enabled very low on-state resistance in the low voltage range (V_{br} < 100 V; e.g., R_{dson} < 6 mΩ @ V_{ds}=30 V), resulting in less heat generation, higher efficiency, and better reliability. The development of the CoolMOS[5] in 1998 enabled a reduction of the on-state resistance by a factor of 5 to 10 compared to a conventional MOSFET (define vertical MOSFET) for the same chip area. Then, the introduction of vertical p-strips in the drift region and the resulting extension of the space charge region also in the horizontal direction, allow a distinct reduction of the device thickness and therefore reduced on-state and switching losses and a lower gate drive power of the Cool-MOS. Today, MOSFETs are available up to a maximum switch rating of 100 kVa.

For higher voltage inputs (> 100 V_{dc}), IGBTs have gained significant importance since their introduction in 1988. Today there are 600 V, 1200 V, 1700 V, 2500 V, and 3300 V IGBTs with currents up to 2400 A. Samples of 4500 V IGBTs have been tested in the laboratories of several device and converter manufacturers. Recently Eupec Power

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[4] R. Pitt, Improving Inverter Quality (2000), Trace Engineering, Arlington, WA.

[5] L. Zverev and J. Hancock, Infineon Technologies Application Note "CoolMOS Selection Guide."

Semiconductors introduced 6500 V IGBTs for currents of 200 A, 400 A and 600 A. Samples of 6500 V IGBT modules are available. The device structure allows punch through (PT) and non punch through (NPT) structures to be distinguished. Both types of IGBTs are offered on the market, up to a voltage of 3300 V. However, there is a trend toward NPT IGBTs, which are inherently more rugged in the short circuit failure mode, more simple to connect in parallel due to a positive temperature coefficient of the collector-emitter saturation voltage, and less expensive to manufacture.

2.1.2 Status of PV Inverters

In addition to device evolution, innovations in converter topologies including Pulse Width Modulation (PWM) techniques, analytical and simulation methods, control and estimation techniques, computers, digital signal processors, Application Specific Integrated Circuit (ASIC) chips, control hardware and software, etc. have also contributed to progress in power electronics. A converter[6] uses a matrix of power semiconductor switches to convert one form of electrical power to another at high efficiency. Converters can inject distortion into the utility, which degrades power quality. Regulations that restrict distortion have become necessary because diode or phase-controlled converters using thyristor-type devices distort line current and thus degrade power quality. Since diode and thyristor-type converters are very common and have increasing quantities connected to utility systems, various types of passive, active and hybrid filters have been proposed to combat distortion problems. IEEE-519(US) and IEC-1000(European) standards have been formulated to restrict harmonic loading on the utility system. The IEEE-519 standard limits harmonic loading at the point of common coupling by the consumer (but not the individual equipment), whereas IEC-1000 restricts harmonic generation by individual pieces of equipment.

The inverter bridge switches are switched open or closed according to various control methods, such as PWM. Since PWM inverters can operate both in inversion and rectification modes, the unit can replace the phase–controlled converter on the line side, mitigating the harmonics and power factor problem. One type of system is the diode rectifier with boost chopper. It shapes the line current to be sinusoidal at unity power factor, but it is non-regenerative. Regenerative connection (positive feedback) in thyristors results in stable operation[7]. A double-sided PWM converter system gives regeneration capability that is important for utility interface.

Recently, attempts have been made to replace the multi-megawatt thyristor phase-controlled cycloconverters for utility use with the IGBT-based three-level converter system. The IGBT system is more economical than the cycloconverter system. Since IGBT's have higher switching frequency and their voltage and current ratings are increasing, there is a growing trend to replace two-level Gate Turn-Off Thyristor (GTO) converters at lower power levels with three-level IGBT converters. Again, as IGBT

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[6] Converter is a general term related to four different conversions (AC-to-AC, AC-to-DC, DC-to-AC, and DC-to-DC). Inverter and rectification are two commonly used terms in PV applications that refer to DC-to-AC and AC-to-DC conversion, respectively.

[7] N. Mohan, et al. *Power Electronics*, John Wiley & Sons, 1995.

voltage ratings increase, there is also a trend to replace three-level IGBT converters by the corresponding two-level IGBT converters resulting in large size and cost benefits. Typically, the two level PWM converters are used in the converters that have low power (200 kVa and less) and three level PWM technique are used for larger power size (250 kVa and above).

In the recent literature, there has been interest in soft switching technology. Traditional converters with self-controlled devices use hard switching. Soft switching of devices at zero voltage or zero current (or both) tends to minimize or eliminate device switching loss, thus providing higher efficiency. Other advantages include elimination of snubber loss, improvement of device reliability, less dv/dt stress on machine insulation, and reduced switch-induced electromagnetic interference (EMI). Of course, using low-pass Inductor Capacitive LC filters can solve some of these problems, but these filters tend to be bulky and costly. Soft-switched converters can be generally classified as resonant link dc, resonant pole dc, and high frequency ac link systems. The resonant link dc can be either the voltage-fed or current-fed type. The former again can be classified as free-resonance or quasi-resonance types, or active or passive clamp types. Soft-switched high frequency ac link systems can be resonant (parallel or series) or non-resonant type. This class has the advantages of transformer coupling, although the number of components is larger. Unfortunately, in spite of a decade of technology evolution, soft-switched converters have barely entered the market place. In spite of the anticipated potential advantages, the need for extra components to clamp the higher switching spikes and the control complexity are likely reasons for their limited success.

2.2 Technologies for Enhancing Reliability

The following paragraphs summarize the areas that are most promising for dramatically increasing inverter reliability while containing cost.

2.2.1 Hard-switching Technology

Figure 2.1 shows the simplest inverter that delivers energy from a battery to a resistive load. The ideal battery produces a voltage, E, that is DC. It does not change with time as illustrated in the time waveform at the bottom left of Figure 2.3. The battery is connected to a bridge of switches. Each switch can be turned ON or OFF. When ON, the switch conducts current in the direction of the arrow.

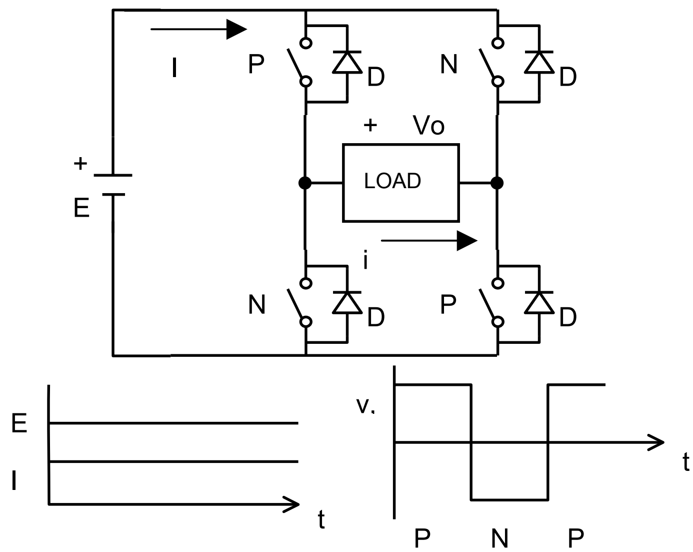

Figure 2. 1. Basic voltage-source inverter with resistive load

The Voltage-source Inverter operates by alternately turning the P and N switches ON and OFF. When the P switches are ON a positive voltage, equal to battery voltage E, is applied to the load; when the N switches are ON the load voltage becomes the negative of the battery voltage (i.e., -E). Thus, a periodic AC voltage is synthesized at the load, which appears as the square wave shown at the bottom right of the figure. In a resistive load, the waveforms of voltage (V) and current (I), are identical. Thus an alternating current results. The current (I) from the battery is DC. In more complex circuits pulse-wave-modulation (PWM) can be used to obtain a sine wave with low (<2%)distortion[8].

2.2.2 Soft-switching Technology

Soft-switching techniques were developed to overcome the fundamental limitations on switching frequency that derive from loss considerations in hard-switched converters. The basic idea is to use additional circuit components, usually resonant circuits, in a way that ensures that voltage or current is held at zero during switching intervals, thus eliminating the switching loss.

Snubbers that are used in hard-switched power converters tend to reduce the rate-of-rise of voltage/current and thus reduce loss in the switch; however, losses then occur in the snubber itself. Resonant snubbers were developed to minimize losses, and were further developed to hold switch voltage at zero during turn-off. Resonant converters, typically the so-called “load-resonant converters,” have been developed for DC-to-DC conversion wherein an inductive capacitive (LC) circuit is used to force zero-crossing where switches are turned ON or OFF.

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[8] S. Atcitty, et al. "Summary of State-of-the-Art Power Conversion for Energy Storage Applications," Sandia National Laboratories, Albuquerque, NM, SAND98-2019, page B-2.

The resonant DC link concept was developed by Divan[9] and has gained wide acceptance. This circuit will be briefly described here to summarize the basic ideas of soft switching. The original version of the circuit is shown in Figure 2.2.

Suppose at a given instant switches PA and NA are ON so as to short-circuit the capacitor. The inductor current *I1* will then rise. If the switches are now turned OFF, the capacitor maintains essentially zero voltage during the short turn-off period. Thus the switches turn OFF with zero loss. Suppose now, at this point, switches PA and NB are ON, to supply current to the load in a manner similar to the basic single-phase inverter. If the inductor current is sufficiently larger than the current delivered to the load, excess current is forced into the capacitor, essentially establishing a resonant oscillation. The capacitor now charges and then discharges to zero volts, provided that the original inductor current is sufficiently large. The switching of devices can now be organized to again short the capacitor and maintain the voltage Vc at zero volts for a short period of time. Loss-less switching can again be performed and the cycle repeated. As a result, the input voltage to the inverter in the basic configuration oscillates between zero and slightly greater than twice the dc input voltage.

Although the switching scheme is now more complicated, it is seen that switching can be organized so as to obtain the waveform of DC bus voltage vc(t) as shown in Figure 2.2. Given this waveform, strategies such as pulse density modulation (PDM) can be used to synthesize an AC voltage vo(t). As illustrated in Figure 2.3, switches PA and NB are switched ON and OFF under zero-voltage conditions to generate discrete positive-voltage pulses in the first half-cycle of output voltage. Then the second half-cycle is synthesized using switches NA and PB.

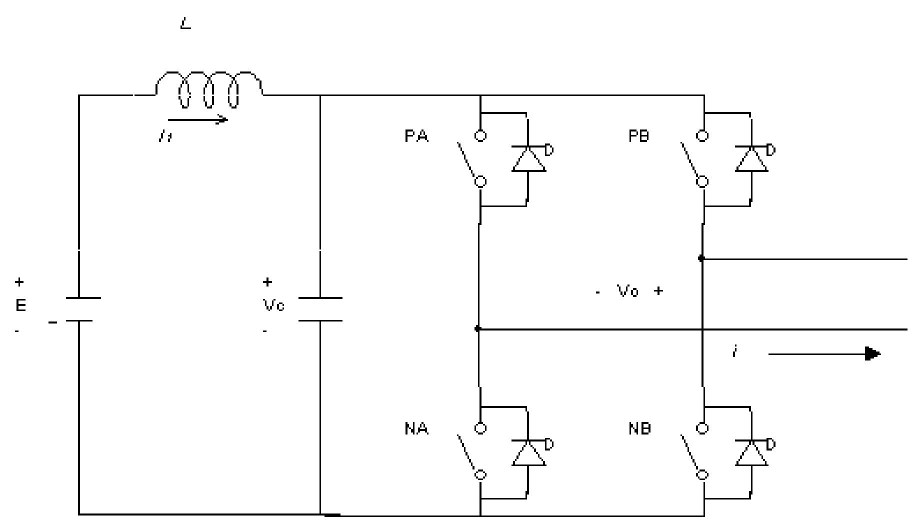

Figure 2. 2. Basic DC-link soft switching inverter

[9] D. Divan, IEEE Transactions On Industry Applications, March/April 1989.

The basic circuit discussed here eliminates switching losses, which permits higher frequency switching. The circuit has the disadvantage of requiring much higher voltage and current ratings for the switches because the switches must carry resonant components of voltage and current. Equally important limitations are the complexity of control and the lack of true PWM capability. Substantial research in this area has led to modifications that have essentially removed the high rating requirement limitation and control schemes have been developed that approach true PWM.

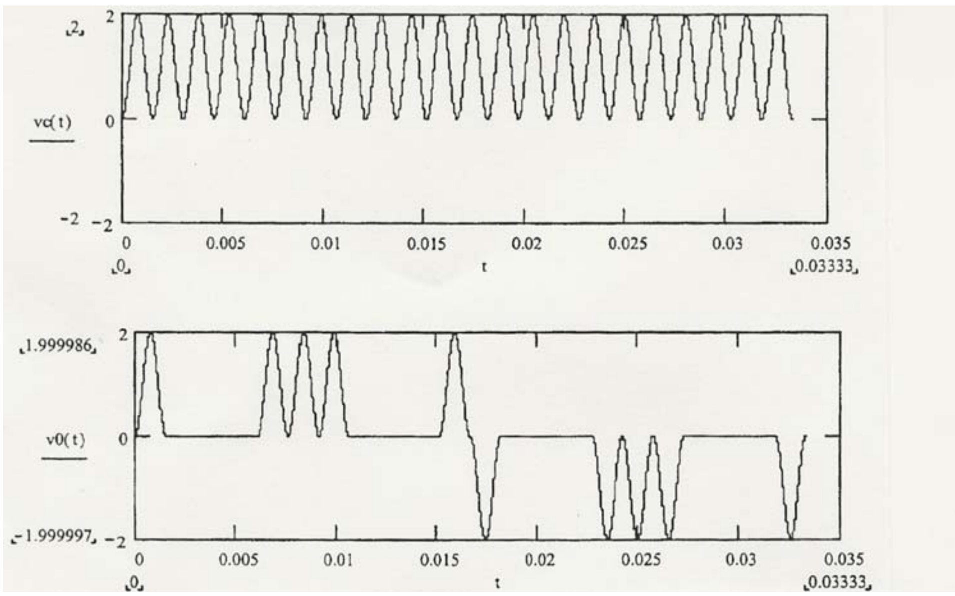

Figure 2. 3. Representative DC-link inverter waveforms under discrete pulse modulation

2.2.3 Hard Versus Soft Switching

A key consideration in custom power electronics is whether to use hard or soft switching. In hard switching, the device is switched on at a time when it blocks full voltage, and off during the time it conducts rated current, whereas soft switching is done at zero current or zero voltage.

A study by Divan, while at the University of Wisconsin in Madison, concluded that soft switching costs more than hard switching. Suppose a switching system is needed for a voltage source inverter meant for motor control. Of the two options, -zero current switching would require the higher current rating. Likewise, a zero-voltage switching system would require higher voltage rating. A higher current rating demands a larger die size and a higher voltage rating requires a thicker drift region in the semiconductor device. So the cost rises for both of the soft-switching schemes, sometimes more than doubling for the same application.

The real advantage of soft switching is much lower switching power loss plus significantly reduced current and voltage rates of change. Power loss is critically important for the design of a high reliability inverter, because it leads to temperature rises in the semiconductor switches and precipitates failure. Although hard switching is more sensitive to circuit parasitic effects (inductance, for example), soft switching tightly couples its lesser parasitic effects to local circuit loops. Hence, even soft switching is sensitive to circuit parasitic effects, and these, if care is not taken, will cause high frequency ringing in switch current waveforms, especially in a zero-current switching converter. The effect on performance is serious, as it gives rise to electromagnetic noise. This circuit parasitic effect will also decrease the turn-off current rate of change, increase the switching power loss, and reduce the switching speed, especially in a zero-voltage switching converter.

Hard switching is simple and less expensive than soft switching. Hard switching is also preferred when it is desired to reduce the size and weight of power-processing equipment. This is also true for DC-AC inverters. With soft-switching more components are needed and they need complex control, hence they are expensive and not very reliable in today's soft-switched inverters. Soft-switching has more potential configurations than hard switching because there are so many ways to implement soft-switching. These include schemes such as load-resonant converter, resonant-switch converter, Zero-Voltage-Switching (ZVS) or Zero-Current-Switching (ZCS), etc., each having distinct tradeoffs in cost, complexity, performance, and reliability.

Hybrid solutions are in wide use in a number of key applications, such as power supplies for computer and communications systems, and are being pursued in automotive electronics and motor control. Called zero-voltage transition switching, one such hybrid is a compromise between true zero-voltage switching and hard switching; the device is switched at zero voltage using auxiliary circuits rather than a fully resonant circuit.

2.2.4 Digital Signal Processing (DSP) Control Methods

A Digital Signal Processing (DSP) controller is the combination of a high-speed mathematical DSP core and memory and a set of peripheral devices on a single chip device. The more appropriate the set of peripherals for the application, the closer it is possible to reach a true single chip solution with no external interface components. Today’s DSP controllers created for complex motor speed and servo control are also ideally suited for renewable energy inverter applications.

The newly introduced low-cost, high performance DSPs, with features such as single-cycle multiplication and accumulation with on-chip PWM mechanism and analog to digital (A/D) converters, provide the Central Processing Unit (CPU) bandwidth and peripheral mix needed to implement sophisticated control techniques required for interfacing with various renewable energy sources. A digital controller has many advantages over its analog counterpart. There are no hardware adjustments, fewer components, less aging effects, and smaller temperature drifts in a digitally controlled system. With a digital controller, adjustment of control parameters for adapting to different electrical environments is easy and flexible. Software damping functions necessary for output filters used in a power converter are easily implemented. Thus no hardware damping components are required for the output filter's resonance. DSP provides other advantages such as full digital control, fewer components, high noise/EMI immunity, high reliability, reduced heating of power switches, lower harmonics, less filtering, faster fault response, no dc components, and higher efficiency. Additionally, it is easy to include other system level functions such as battery charging, power factor correction, reactive power compensation, fuzzy logic control, parallel operation, and on-the-fly frequency change to adapt to different environments and applications. Secure remote communication, data acquisition and display, device overload protection, maximum power tracking, and state control can all easily be implemented.

Lower Losses. DSPs reduce heating of power switches because DSP can optimize the switching frequency on the fly based on the mode of operation of the system and also can change the switching frequency on the fly. This means that a higher switching frequency can be used to ensure continuous current and smaller magnetic effects for the renewable sources interface. A lower switching frequency for battery charging then minimizes the switching losses and maximizes the system efficiency.

Traditionally, a PWM converter is treated as a continuous system when the control system is designed. That means that higher bandwidth and higher switching frequency are required with an analog controller; this leads to high switching losses. With DSP control, PWM converters can be treated as a discrete system when the control system is designed. This means that to achieve the same performance as an analog control inverter, lower switching frequency is allowed with the same filter parameters. This is another approach for reducing the switching losses.

Flexibility. Because of the advantages of digital control over analog or analog/micro-processor hybrid control, it is obvious that **a DSP controller is the choice to control a power converter system for renewable energy sources**. DSP-controlled, universal power converter systems can be configured for multiple renewable energy sources (solar, fuel cell, micro-turbine, flywheel, wind, etc). They also can be configured for multiple applications (grid-tied, off-grid, uninterruptible power supply (UPS), voltage sag compensator, active power filter, harmonic power compensator, etc). They could have the same hardware with specific dc interface software (kernel) for each renewable energy source. The interface software (kernel) could be configured by user/integrator to work with a specific renewable energy source or in a specific application. Because of the universal configuration, the production volume of such power converter systems could be high.

Fewer Parts. With advanced DSP control, low frequency passive filter and high frequency filter damping circuits are not required for the proposed inverter. This results in a simple system configuration, high reliability, low cost, smaller footprint, and lighter weight. For example, the rfi (radio frequency interference) filter can be smaller and less costly.

Application of DSP. The potential commercial applications for this technology are enormous. Universal features of DSP could be extremely useful for greatly increasing the quantity of power converter systems manufactured, thus improving the quality of the power converter systems. That is, a single product could have more applications leading to higher sales volume.

2.2.5 Universal Software Modules

Each new generation of power electronics technology makes increasing use of software operating on embedded microcomputers. In early generations, software was used for status monitoring, high-level control and external communications functions. Today, software is critical to protective relaying functions required for grid interactive operation. In the next generation, software running on high speed digital signal processors will perform closed loop feedback control and will directly control the switching of the power devices (e.g., FETs and IGBTs). With this increase in software's importance there is an increase in its size and complexity. Unfortunately, much of today's software suffers from reliability problems and it is difficult to maintain. These problems stem from the fact that much of software is written by power electronics engineers or control system engineers who have limited training and background in modern software engineering practices.

2.2.5.1 Reusing Software Designs

In addition to the reliability and maintenance problems associated with current software design practices, there is also a lack of design reuse. In some cases the software for a new power electronic converter is designed without reference to previous designs. In other cases an attempt is made to build upon previous software but the structure (or more accurately, lack of structure) of the software makes this a time consuming and error-prone process. In many cases, the new software is initially less reliable than the software it was based on. In some cases key algorithms become corrupted because changes are made that affect undocumented, but critical, functions of the software implementing the algorithm. Part of the solution to these issues is to adopt modern software engineering practices based on modular software.

The benefits of designing modular software are well documented and known throughout the software industry. The benefits include:

- easier software reuse;
- improved software documentation;
- easier "porting" (when written in modular format, S/W can be "ported" to different DSPs and different applications);
- the ability to "build-up" a system from small "chunks" of code rather than monoliths;
- easier and faster debugging;
- easier and faster development and
- software standardization.

2.2.5.2 Modular Software

Easier software reuse means that subsequent software projects should proceed more quickly because engineers can combine already coded modules with new application modules thereby reducing development costs and hastening time to market.

The external software documentation of modular designs is better because the modules themselves have clear functional responsibilities and interfaces. Better documentation will persuade software engineers to make use of the code because they will be more likely to understand and trust it. This will also reduce costs and time to market.

With modular software, porting to other hardware platforms (targets) becomes faster and easier because of the clear distinction (modularity) between target-specific and general purpose code.

Debugging is also easier with modular code as the interfaces between the modules provide well defined “test points” when using a debugger. The test points are places where the results of calculations and peripheral operations can be viewed, verified and altered in order to exercise the software.

The time required to develop software is drastically reduced using a modular approach. Multiple engineers can each work on a different module in parallel because the interfaces between the modules are well documented and understood. Faster development means faster time to market.

The ultimate goal of modular software is standardization. This includes a standard

- requirements specification process;
- design process and techniques;
- set of document templates;
- high-level language (i.e., ANSI C);
- coding style and naming conventions and
- set of algorithm implementations.

All of these standards work together to increase design/code reuse, robustness and reliability, and reduce development effort, costs and time to market.

2.2.6 Made-to-order Power Electronics

With advances in computer aided design it is now possible to custom-make power electronics semiconductors and modules. These can have

- inclusion of application information in the switch design process,
- design for end of life,
- de-rating the Safe Operating Area (SOA) as inverter ages, and
- minimal on-resistance.

“Made-to-order power electronics[10] is a joint custom approach that includes collaboration between semiconductor device manufacturer and product designer so that the design can fit the product to the application. “Rather than work in isolation, makers and users can together optimize each switch for its intended use throughout its life. This strategy has evolved over the past 10 years. Its focus is on two system fundamentals: performance and reliability. In pursuit of the first, the goal is to minimize the power loss in power devices” for a given application by minimizing such parameters as on-state resistance. The reliability goal is to extend the devices’ operational life by, for example, reducing the thermal stress of switching at high frequencies. “High” typically means over 500 kHz in power supplies for computer and communications systems and over 1 kHz in power inverters for traction systems. These goals apply to any type of power semiconductor, including the commonly used MOSFETs and IGBTs.”

“An important goal for this strategy is to have manufacturers make it possible to de-rate power electronic devices over time so as to avert premature failure. The de-rating would involve adjusting the safe operating area (the current-voltage boundary within which the device can be operated safely) as the device ages- an approach called design for end of life.”

“An early beneficiary of the custom approach is an integrated IGBT inverter for traction from Asea Brown Boveri (ABB), Baden-Dattwill, Switzerland. The customer was ADTranz, a rail car manufacturer in Zurich, Switzerland. Circuit designers and device manufacturers from different departments within ABB tailored the design to ADTranz’s needs.” They “individually optimized each switch, plus the associated parallel diode that provides a current path when the switch is off, plus the entire package. What they produced was a switch that operated at frequencies over 1 kHz, higher than the typical few hundred hertz in earlier systems, so that the system was reduced to about one-third of its original size.”

Traditionally in either use, hard or soft switching, “it has been the circuit designers who model the load, determine the applied voltage, and define the application requirements.” Next the circuit designers have selected a control technique – pulse-width modulation, for example – and designed the circuit. Finally they have determined the ideal voltage and current ratings and picked a power semiconductor switch from data sheets.

“However, with custom power electronics, it is the device designers who determine the specifications of the device. Then they optimize it based on a detailed circuit simulation, taking into account such applications constraints as load variation, switching scheme, anticipated thermal stress as a result of overheating, and ambient temperature. The simulation analyzes the device’s physical model with either an analog simulator such as Simulation Program with Integrated Circuit Emphasis (Spice)-type analysis (in which the circuit is represented by lumped components) or by its simplified behavioral model, which replaces the complex Spice circuit with simpler analytical expressions.

[10] K. Shenai. “Made-to-Order Power Electronics,” University at Chicago, IEEE *Spectrum,* July 2000.

Such treatment applies realistic stresses to the device simulation without incurring the complexities of simulating full circuit operation.”

3 Status and Need for Corporate Plans and Infrastructure

There has been a lack of a structured management approach to the development of PV inverters. This section addresses some of the standard best business practices that are essential for the development of a successful product. Any government involvement in the development of a 'next generation' inverter should ensure that prospective bidders have as many of these best business practices in place as possible.

3.1 Developing a New Product

Some of the basic issues related to the development of any cutting edge product are discussed below. Frequently neglected issues include the following.

- *Product fit in long-term company business plan*. The product must be consistent with what the company normally does. This means that adequate marketing tools and marketing plans are available, that the technical development skills are in-hand, that adequate manufacturing and maintenance facilities are available, and that the resources necessary for a long-term development project exist. The development of a revolutionary (i.e., next generation) product has some risk. This implies that success is probably not just 12 months off. One author[11] notes that the development of new products can take ten years. While most companies that are developing or contemplating the development of PV inverters are not starting from zero (and thus a shorter development time is anticipated), they must have financial resources and management commitment for a multi-year effort.
- *Market research*. Before anything else, a complete research of intended markets must be accomplished. Both the need for and growth opportunities of the product must be clearly understood. A misjudgment of either of these can cause faint-heartedness in management or even the collapse of smaller companies or business units.
- *Innovative product*. The manufacturer must clearly understand what makes his product different from others, satisfies a need, and thus creates a market in the distributed energy area.
- *Marketing strategy*. The best product will not be successful without competent marketing to the appropriate audience. The manufacturer must focus on a profitable product and have a marketing plan as a part of the original product development plan. Planning and funding for marketing are a necessary part of any product development.
- *Versatility*. As the 'systems engineering' progresses, the direction of preconceived notions of success should not restrict the product. During the course of product development the direction may be changed. Institutions frequently resist this change with a desire to continue with the tried and proven.

[11] T.D. Kuczmarski, *Managing New Products – The Power of Innovation*, Prentice Hall, Inc., 1992.

Attention to the above issues greatly enhances the probability of success for new product development.

3.2 The Need for Systems Engineering

Photovoltaic power systems are still an emerging technology. The effort planned herein, to develop the next generation photovoltaic inverter, thus requires careful planning and understanding of requirements. It is imperative that a systems engineering approach be used for the inverter design. Systems engineering is primarily concerned with problem stating, not problem solving[12]. Problem definition should be accomplished in simple language, avoiding ambiguity and the premature selection of a solution. In this process one must determine:

- *What the system is supposed to do*. For example, if the answer is simply to provide refrigeration for vaccine, then no failures are permitted, and it is known immediately that the system must be over designed to provide the proper safety for the vaccine.
- *How performance will be judged*. For example, in a navigation system the loss of a single vessel will be judged a failure.
- *What is available to build the system*. For example, for small stand-alone systems, one must understand the limitations of batteries in Third World countries, and the development status of components such as hybrid inverters (i.e., are you fielding a beta unit?).
- *Methods of resolving conflicting performance specifications*. For most systems there is a tradeoff between acceptable cost and high reliability. An example of an additional tradeoff for an inverter would be weight versus peak power.
- *Testing requirements*. All testing requirements must be identified early in the process. For example, if an inverter is required to reduce rfi (radio frequency interference) levels to be compatible with FCC Part 15 requirements, then rfi filters must be incorporated into the design. In addition to requiring the design of the inverter to optimally accommodate filters, the need to achieve FCC compliance could demand other design considerations such as shielding, lower switching frequency, and component placement.

From the problem definition emerges a specification, a decision on the technology approach, identification of technology challenges, and a test plan.

Design. A key element of successful systems engineering is the involvement of all stakeholders (e.g., manufacturer, suppliers, distributors, sales staff, users, funding authorities) in the development of requirements and the preliminary design. At least one design option should be thoroughly examined by all stakeholders before a prototype is built. Thus potential additions or changes to the design will not challenge “all the work we have done.”

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[12] W. Chapman, et al. *Engineering Modeling and Design*, CRC Press, 1992.

Some key elements of the design process are:

- preliminary design and drafting
- modeling
- prototyping
- subassembly testing
- failure analysis, and
- design review.

3.3 Present Manufacturing Barriers to 10-Year Lifetime

The following discussion addresses well-understood barriers to a 'next generation' PV inverter. Many of these issues refer to problems associated with small companies. This is not meant to imply that smaller companies cannot play a pivotal role in the development of a 'next generation inverter,' only that they must either overcome these problems or team with a company that has solutions in hand.

Aside from poor design, the failures that may be anticipated during the lifetime of each inverter are due to the inevitable component variations in materials and workmanship, along with unexpected combinations of operating conditions. Without efficient manufacturing techniques and active quality control measures, these failures will ruin the reliability record of an otherwise excellent inverter.

3.3.1 Inflexible Design Leads to Low Volume, Small Manufacturers

Today's power converter systems for renewable energy sources are uniquely designed for each energy source and only suited for one kind of energy source. This translates to low volume and low quality. Because of low volume, mass production techniques are not used. The low volume of power electronic converter systems produced for renewable energy sources restricts the manufacturing base to small suppliers without sophisticated research and reliability programs or sophisticated manufacturing methods. The volume of inverters to be manufactured also affects the cost of purchased components and the efficiency and accuracy of the production process. The solution is a design that applies to multiple markets.

3.3.2 Inadequate Corporate Structure

Major considerations in manufacturing a high quality product are discipline and creativity. Small manufacturers typically do not have the organizational infrastructure and the continuous efforts that are required to foster these traits.

There are numerous aspects to consider when attempting to effectively solve the technical problems of PV inverters. They include: (1) having access to the necessary technical information and skills to accurately analyze the details of the problem, (2) having a disciplined process for analyzing the data, (3) being able to identify solutions and evaluate which is best, (4) having the authority to implement the solution, and (5) knowing how to effectively plan the implementation of the solution.

3.3.3 Minimal Staff with Inadequate Time

In most small companies, manufacturing engineers may spend more than 90 percent of their working time troubleshooting. They have the mentality of "quick fix," because they have minimal staffs with inadequate time. The development engineers are frequently under intense pressure to bring products to market as quickly as possible, often because of the unrealistic schedules imposed by management. Shortsighted attitudes are frequently imposed on engineers. This must be controlled because time-to-market is not just design time, but also the time it takes to get a product into the customer's hands at a competitive price. **If it takes multiple redesigns** to meet specifications or to lower manufacturing and test costs, and/or to fix glitches because of inadequate design verifications, **the advantage of rushing a design is negated**. The solution is working with a company that has adequate personnel or can acquire additional personnel that have a consistent source of development funding.

3.3.4 Shortage of Sophisticated Test and Assembly Equipment

The typical approach to quality control used by smaller manufacturers relies upon test, assembly equipment, and inspection. Proper testing requires sophisticated test and assembly equipment that smaller companies cannot afford. Typically they do not use automatic test fixtures for printed circuit boards because the low volume does not merit the expense of their development. Also an expensive automated production line is out of the question for most PV inverter manufacturers because of low volume and high cost. Finally, most PV inverter manufacturers do not have the experience for automated production lines. The solution is working with a mature manufacturing company that has demonstrated these capabilities.

3.3.5 Minimal Pre-field Testing

Because all PV inverter manufacturers face the pressure of time-to-market, they tend to bring the product to market with minimal pre-field testing. Accelerated testing methods are not widely implemented in this industry. Sometimes testing and test methods are not clarified during the development of the product modules. Electrical, mechanical, material, physical, and environmental tests are not specified in the early design stages. The design team does not implement the appropriate application of concurrent engineering and methods when the design criteria are reviewed and analyzed during the development process. Shortchanging the evaluation of a product before release can result in the release of a flawed product. The solution is a requirement for adequate development testing in the schedule.

3.4 Some Manufacturing Issues

Even well designed products may not have suitable reliability if the existing manufacturing processes are not well defined and repeatable. The following paragraphs address some of the most important of these.

3.4.1 Purchasing

For small-lot manufacturing, components are purchased in small quantities, often fewer than 100 pieces at a time. In order to keep costs down, it becomes necessary to competitively search for the best buy on these components. The result is that inverters will be built next month with components from different manufacturers and with lot codes different than those now being installed. While the design of an inverter is intended to accept the variations anticipated from one part to the next, the wider the variation of purchased components, the more frequently a new problem will surface, requiring action to maintain the required performance and reliability.

3.4.2 Assembly

Fully trained assemblers are one key to maintaining integrity and reliability in the manufacture of inverters that have been carefully designed and documented. The highest possible reliability depends on consistent manufacturing. Because lower cost can result from off-shore assembly, it has been said that the real benefit of automated assembly is repeatability.

Limited production runs also result in one workspace being utilized for a variety of tasks on a range of product. It becomes necessary to take down one setup to prepare for the next task, introducing another chance for unexpected variations.

3.4.3 Quality Control

A thorough quality control program involves in-process inspection and documentation of failures. The result of a good quality control program, if not to totally eliminate all failures, is to advance the detection of problems from end-use failures to detection at the factory, and to advance the detection of these factory failures from the latter stages of production, such as burn-in, to progressively earlier stages – final test, sub-assembly test, and inspection. The earlier these are detected, the lower the probability of inverter failure during end-use.

A common pitfall is that the success of inspection makes it appear as though inspection is unnecessary. When resources are limited and product quality is very good, inspection may be de-emphasized, only to regain attention when failures have escalated.

Limiting the scope of an inverter manufacturer's quality control program may appear to be a cost cutting measure. This is an illusion to be avoided. Inspection and failure reporting will provide a cost benefit by:

- reducing manufacturing rework,
- increasing test throughput,
- improving inverter MTTF, and
- reducing customer support time due to failures.

3.4.4 Inspection

Some elements of manufacturing may cause failures during test or burn-in, or even worse, cause latent deficiencies in an inverter that may not surface during test and burn-in, only to result in failures after installation. When assemblies are inspected prior to testing, common errors can be identified, corrected, and avoided in the future, and the MTTF of the final product will be enhanced. Also, the root cause of potential failures can be determined and eliminated, for failures that might otherwise appear to be due only to random component failures.

3.4.5 Failure Reporting

The documentation of all failures during test and field operation of the inverters is used to identify trends and to record corrective actions taken. No matter how comprehensive the design, documentation, and training program, there will be details, perhaps critical nuances of component requirements and the assembly process, which no one realized or thought to explain until these failures occur.

Frequently, when resources are limited, the first thing to be compromised is the documentation process. The question implied will be, "Our product is working fine. Why should we spend our time writing down what we did wrong?" There are good reasons to maintain accurate and comprehensive failure documentation. Some of these reasons are discussed in the following paragraphs.

3.4.6 Trend Identification

Identification of failure trends is a very useful tool for achieving the highest possible reliability. When failure reports are taken diligently, the data may be used to improve assembly and sub-assembly accuracy and quality, which will be seen in improved inspection and test results and reduced rework and burn-in failures. When a particular failure is noticed to occur repeatedly, Quality Control, Production and Engineering can work together to determine the root cause of the failures and take corrective action to prevent these failures from recurring.

3.4.7 Field Returns

When field returns do occur, the records may be reviewed to determine what rework and failures have occurred previously on that same unit. In this manner, process errors and failures that are determined to increase the likelihood of future failures may be identified and eliminated.

3.4.8 Training

When a new product is ready for production and the sales force has customers waiting, there is great pressure to start shipping as soon as possible. All too often, the production process begins before the beta testing requirements are satisfied, and inverters are shipped before everyone has received adequate training. As the watchful eye of supervisors and engineers shifts to new programs, the assemblers and technicians, who have not been trained to identify some critical details of their jobs, begin to, unknowingly, deviate from the process that was intended.

3.4.9 Personnel Rotation

Limited resources often lead to the rotation of personal from one task to another. This can result in the assignment of an assembler or technician to a task for which he or she has not been fully trained, or for which they have not had the experience to complete accurately without greater supervision. Quality is compromised when less experienced workers perform operations without additional training, supervision, and inspection.

To fully appreciate the impact of limited resources, one may consider the impact of manufacturing small quantities as discussed elsewhere in this section. When resources are limited and personnel are shifted away from one product and back again later, that has the same impact as building the inverter in even smaller production runs.

3.5 Testing

The design goal of achieving an MTTF of 10 years addresses the random failures and end-of-life failures of components within the inverter. However, the manufacturing process of both the components within the inverter, and the inverter itself, will inevitably produce some units with latent faults that only manifest after operation of the inverter. No matter how high the design MTTF may be, the actual performance of the inverter in use will achieve this MTTF only if these latent failures are precipitated during a thorough testing before it leaves the factory. Production testing may be categorized into 3 distinct groups. These are circuit level test, final assembly level test, and burn-in.

It is by this monitoring and improving process that the effect of production test is extended beyond just fixing broken parts. Ultimately, through this process, the factory personnel continually act together to eliminate failures even at the production test level, and also to extend the scope of this testing as failures appear in field use.

3.5.1 Highly Accelerated Life Testing and Screening

In recent years, the test techniques known as HALT[13] (Highly Accelerated Life Testing) and HASS (Highly Accelerated Stress Screening) have been gaining advocates and practitioners. These test methods, quite different from standard life testing, design verification testing and end-of-production testing, are becoming recognized as powerful tools for improving product reliability, reducing warranty costs, and increasing customer satisfaction. HALT is a test that is performed on a product as part of the design process. It can be performed on circuit boards but more typically, it is performed on a product when pre-pilot or pilot run units are available, before the design verification testing begins. During HALT, a product is stressed far beyond its specifications as well as far beyond what the product will encounter in a typical use environment. The actual functional and destruct limits of the product are found and pushed out as far as possible. These limits are used as the basis for HASS testing, which is a screen of product to limits that are far below the destruct limits determined by HALT. As with all test-screening methods, HASS consumes lifetime and thus one may desire to limit HASS to a relatively small sample size.

3.5.2 Circuit Level Test

Each individual sub-assembly, such as a circuit board, wire harness, etc., has the potential to cause a failure of the inverter. By testing these sub-assemblies and performing repairs as needed prior to assembly into an inverter, potential failures during final assembly level test may be greatly reduced. This is very important because failures of the inverter, even while the unit is still at the factory, have the potential to over-stress other components within the inverter, setting the stage for additional latent failures that may occur in field use.

3.5.3 Final Assembly Level Test

These tests are designed to activate all of the circuits and features of the inverter. The results are both functional verification and parametric verification. At the conclusion of this test, a data sheet should be complete, which indicates that all of the inverter functions are performing correctly, and that all of the operating parameters of the inverter have been measured, compared to the required performance specifications, and are acceptable.

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[13] G. K. Hobbs, *Accelerated Reliability Engineering, HALT and HASS*, John Wiley & Sons., 2000.

The required performance specifications may be the same as the published performance specifications. In many cases, the factory test specifications may include limits that are more stringent than the published specifications.

3.5.4 Burn-In

No test program is complete without adequate burn-in. During burn-in the inverter is operated continuously for a period of time so that any premature failures due to workmanship or materials will occur prior to field use. In the case of a failure during burn-in, the unit is repaired, re-tested, and submitted to burn-in again. It is very important for Quality Assurance and Engineering to monitor these failures.

Burn-in should be designed to stress all of the electronic components in the inverter to their maximum normal operating temperature. Power electronic components should be stressed to their maximum normal operating voltages and currents. Burn-in may be performed at conditions beyond normal operating conditions such as input voltage or output current in order to accelerate possible failures due to faulty materials or workmanship. In addition, burn-in may be performed with cooling fans retarded or disabled in order to achieve maximum desirable component temperatures.

One of the greatest stresses on power electronic devices occurs during the start-up and shutdown of the inverter. It is best to cycle the inverter on and off after the maximum desired temperature is reached. The shut-off of an inverter during burn-in may be initiated through its own protection circuitry such as over voltage, over current, and over temperature. The required automatic re-start of the inverter after each fault detection will then also be verified.

3.5.5 Beta Testing

Beta testing is performed on engineering prototype units. This testing program is a major part of the design phase. Unlike production testing, where the product performance is essentially compared to that of a known good unit, beta testing begins with a prototype that inevitably has a variety of defects and design flaws. The beta test program involves many cycles of test, modification, and re-test. Ideally, the beta test program continues until Engineering, Production, Quality Assurance, and Management are all in agreement that the product performance is acceptable and reliable, and that the product is manufacturable at a cost that supports the market pressure.

During beta testing, the following expectations are present:

- Performance Requirements
- Reliability Goals
- Cost Goals
- Deadlines.

Each of these goals exerts pressure on the designers to compromise the attainment of the other goals. Some degree of compromise is always required. An atmosphere of open and clear communication of these goals at the onset of the design program will establish the best environment for compromise of various issues that arise, without compromising the inverter reliability. The importance of honest discussion of the status of beta testing, and of flexibility in program demands, cannot be overemphasized.

3.6 Design for Manufacturability

The ultimate goal of engineering is always to support manufacturing. The engineering design must be communicated accurately to Production. Production must accurately communicate any difficulties and anomalies to Engineering. The design changes that arise out of these needs must then be communicated back to Production.

Once the design process has resulted in a comprehensive set of design documentation, Production and Engineering work together to complete the tooling, fixtures, test procedures, and workplace setting to efficiently and accurately manufacture the inverter. It is imperative that these systems be documented in writing, and that changes are reviewed by both Production and Engineering.

3.6.1 Engineering Changes

When Production experiences a problem that cannot be remedied by attention to production processes, they must communicate this problem to Engineering. This communication is best done in writing. An Engineering Change Request (ECR) form may be used for this process. This form should include information regarding the nature and extent of the problem, when it began, and any proposed solution that may be apparent.

Changes to the design should not be incorporated into the inverter until Engineering has reviewed them for possible conflicting effects on other performance parameters and reliability. When approved by Engineering, design changes may be communicated to Production by the use of and Engineering Change Order (ECO). This type of document indicates that the inverter will now be built with the specified change from the previous documentation. The ECO should detail the change to the design, and specify when to implement the change.

3.6.2 Work Instructions

Often, during beta testing and pilot production, Manufacturing will generate work instructions for use in training assemblers and technicians how to build and test the inverter. Sometimes production problems arise that do not require engineering change, but rather, the manufacturing process may be modified. It is desirable for Engineering to review these changes to check for unexpected negative effects on other aspects of the inverter.

4 Summary

Photovoltaic inverters are the most mature of any DER inverter, and their mean time to first failure (MTFF) is about five years. This is an unacceptable MTFF and will inhibit the rapid expansion of PV. With all DER technologies, (solar, wind, fuel cells, and microturbines) **the inverter is still an immature product that will result in reliability problems in fielded systems.** The increasing need for **all of these technologies** to have a reliable inverter provides a unique opportunity to address these needs with focused R&D development projects. The requirements for these inverters are so similar that modular designs with universal features are obviously the best solution for a 'next generation' inverter.

A 'next generation' inverter will have improved performance, higher reliability, and improved profitability. **It is not simply an improved version of what has not worked well; it is an order-of-magnitude move forward**. Such a development will have risk. Success is not guaranteed. Sandia National Laboratories has estimated that the development of a 'next generation' inverter could require approximately 20 man-years of work over an 18- to 24-month time frame. Companies with existing design and manufacturing experience in power electronics could accomplish the task with fewer resources. The investment, however, is not small for most companies interested in the task. For that reason a government-industry partnership will greatly improve the chances of success.

Point One: *The pooling of resources from several DER programs can greatly accelerate the development of high performance, high reliability inverters.*
Many of the problems that exist with inverters are known. These include design problems, manufacturing flaws, and poor management practices; these are the issues that the current inverter initiative intends to address. The next level of reliability will be reached by extensive analysis of field data that identifies continuing inverter problems. There is still inadequate field performance data. As mentioned in Section 4, failure reporting and trend identification are elements associated with mature manufacturers and thus some of the necessary data could result from this program. Further information will be included in the Sandia reliability data base that is currently being developed. The acquisition of adequate field performance data will require large numbers of fielded product.

Point Two: *The need for credible reliability data for field-aged systems needs to be aggressively pursued so that failure modes can be identified.*
There are emerging technologies that can be used to greatly enhance the performance of inverters including digital signal processing (DSP), made-to-order power electronics, and new control methods such as dead-beat or repetitive control. Additionally, new approaches to software such as building reusable modules will greatly accelerate new applications and the development of new products. **DSP** performs extremely fast signal analysis that provides inputs to low-level decisions (i.e., control of power bridges) and to higher-level decisions (i.e., control of battery charging). This approach to inverter control will result in fewer parts and longer life. DSP controllers are now available in chips, making digital signal processing available to low cost inverters. **Made-to-order power electronics** is a capability that results from the fact that power electronic

switches, designed with software, can now cost-effectively tailor a new power module for smaller markets. With the help of DSP, the inverter can now be designed for end-of-life and operating curves can be adjusted as the inverter ages. The inverter layout can also be tailored to the application, thus minimizing parasitic losses, optimizing heat transfer, and resulting in faster switching and lower heat losses. **New control methods** may result in a lower switching frequency. This approach counts on improved DSP control to ensure power quality while limiting the size and cost of the inverter magnetic components.

Point Three. *Recent technology and design advances will enable designers to make dramatic advances in performance and reliability, and lower cost. These are not, however, a simple extension of previous engineering efforts. They differ dramatically in their nature and in the skills required for successful implementation.*
Experience with mature products that have had successful development, marketing, and production point to several characteristics that greatly enhance the probability of success in new product development. Some of the most important issues include the utilization of a systems engineering design approach, an in-place quality program, ISO certification, adequate facilities for manufacturing, and testing. In general these practices involve planning ahead, structure, accurate documentation, and equipment/ manpower capability. Many other issues are listed in the report body. These characteristics are most likely to reside within mature companies with an established track record of manufacturing.

Point Four. *Any government involvement in the development of a 'next generation' inverter should ensure that prospective bidders have as many of these best business practices in place as possible.*

Final Thoughts. There must be more than one development area because of the different sizes of potential applications. Two sizes that come to mind immediately are the residential (2-10kW) and small industrial (20 – 100kW) inverters. Most of the work for the different sizes will be very similar. The concepts, for example of modularity, control methodology, DSP control, etc., will be designed to be transportable from one design to the other. The first R&D effort could be targeted at any size desirable. However, the best approach is to target the size for which the greatest market exists today -- residential. This will allow the manufacturers to get more rapid field performance feedback and thus improve the design even more. In the final analysis targeting the larger market first may result in an earlier delivery of a more robust product for the industrial market.

What makes this initiative, the development of a 'next generation' inverter, timely is an increasing market and recent technology advances. Previously the DOE approach to improving inverter performance was limited to participating with small business in the incremental improvement of their product. At this time the market has expanded to the point where larger companies are interested. The timing is right for a major DER inverter initiative that will result in a quantum leap forward in technology.

5 Glossary

MOSFET	metal-oxide semiconductor field-effect transistor. A voltage gated-on device with positive temperature coefficient and fast switching times of as little as tens of nanoseconds.
GTO	gate-turn-off thyristors. A current pulse gated-on device with turn on times as low as a few microseconds and most useful for high voltage applications. Can be gated off with large negative voltage.
IGBT	insulated gate bipolar transistors. A voltage gated-on device with turn on times of approximately 1 microsecond and modest (2-3 volts in 1000 volt device) on voltages.
CoolMOS	An MOS device with on resistance equal to 20% of previous designs.
PT	Punch through process, historically used to make IGBTs, relies on a heavily doped P+ substrate with an N-epi grown on the surface. Fast turn-off slows as temperature increases.[14]
NPT	Non-Punch Through process relies on the use of a lightly doped homogenous N-substrate, no epi and a MOSFET structure fabricated on the surface. Fast turn-off is nearly independent of temperature.
phase controlled inverter	A method of control applied to SCR converters that varies the application of the gating signal in the positive half cycle and depends on reverse voltage to turn-off the SCR.
diode rectifier with boost chopper	A circuit that utilizes a switch to double the dc voltage by alternately charging two series connected capacitors.
cycloconverters	A thyristor ac/ac direct-conversion converter with multi-phase input that converts high power levels, typically in excess of 100 kW[15].
GTO	A thyristor that can be turned on by a short current pulse and turned off by a negative gate-cathode voltage.
snubber	Typically a diode that is placed across a switch to suppress undesirable transients and to eliminate ringing.
PDM	Pulse Density Modulation.
DSP	Digital signal processing is the processing of number sequences to estimate the characteristic parameters of a signal. DSP is not new. The ability to have DSP on a single chip is new and extends DSP techniques to new applications.
rfi	Radio frequency interference is an undesired byproduct of switching that may interfere with the operation of nearby electronic components.
harmonic	A signal component whose frequency is a whole multiple of the fundamental frequency (60 Hz for power systems).
power factor	The ratio of true power to apparent power.

[14] Application Note APT9805, "Performance Comparison of the New Generation of IGBTs with MOSFETs at 150 kHz, Advanced Power Technology.

[15] J. G. Kassakian, et al. *Principles of Power Electronics*, Addison Wesley Publishing Co., 1991.